Flow-Structure Interactions in Presence of a Free-Surface

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LONG-TERM GOALS

1. Determine the space-time structure of vortex formation from bodies adjacent to a free-surface using quantitative imaging; relate this structure to the instantaneous loading.

2. Employ both externally-controlled and elastically-mounted systems to assess the mechanisms of energy transfer between the fluid and the body, with the eventual intent of implementing active and passive control.

OBJECTIVES

1. Determine experimentally the relationship between: (i) mechanisms of vortex formation from a cylinder in presence of a free-surface; and (ii) unsteady loading on the cylinder.

2. Develop and implement new techniques for acquisition of instantaneous, quantitative images of vortex patterns that dictate unsteady loading.

APPROACH

Quantitative imaging of vortices and simultaneous force measurements define the physical origin of vortex-induced loading. Image analysis includes: topological classification of vortex patterns in space and time; and identification of vortex contributions to forces via theoretical models. These approaches employ integrated experimental systems involving either computer-controlled or elastic motion of the cylinder, high sensitivity force transducers, laser illumination, and dual-camera cinema techniques. Extensive post-processing of images provides space-time representations of the vortex patterns in relation to the loading.

WORK COMPLETED

Basic classes of flow-structure interaction in presence of a free-surface have been investigated using an integrated experimental approach. It involves space-time imaging, via high-image-density particle image velocimetry, and simultaneous two-component force measurements. For the case of a cylinder undergoing transverse oscillations in a steady current, basic modes of vortex formation and transformation between these modes have been characterized for a fully-submerged cylinder;

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preliminary experiments with an adjacent free-surface have been initiated. Vortex formation due to in-line oscillations of a cylinder in presence of a steady current, which simulates long wave motion past a stationary cylinder in current, has been addressed. New types of locked-on states have been related to the instantaneous loading of the cylinder. Emphasis has been on the case of a fully submerged cylinder; experiments in presence of an adjacent free-surface are underway.

Free-surface wave interaction with a stationary, horizontal cylinder has been investigated for the case of a sufficiently high Keulegan-Carpenter number such that multiple processes of vortex formation occur during a wave cycle. Patterns of vorticity have been related to the unsteady loading on the cylinder. For the case of a free-surface wave incident upon a vertical, elastically-mounted cylinder, which is free to move in any direction in a horizontal plane, the transient development from unidirectional to two-dimensional trajectories of oscillation has been characterized. Initial quantitative imaging of the corresponding vortex patterns has been achieved.

Development of new experimental techniques has involved continued refinement of an orthogonal imaging system that allows space-time imaging of the development of spanwise and streamwise vorticity concentrations, with the intent of determining the influence of three-dimensionality on the instantaneous loading of oscillating cylinders.

RESULTS

Wake from a Transversely Oscillating Cylinder: Abrupt Changes of Loading and Energy Transfer

Large-amplitude oscillations arising in an elastic system having low-mass damping is simulated by controlled oscillations of a cylinder in the transverse direction in presence of a steady current. Simultaneous imaging and force measurement reveals the relationship between the instantaneous patterns of vorticity, streamline topology, and cylinder loading. When the cylinder oscillates at a fixed frequency near the Kármán frequency, an abrupt increase in magnitude of the fluctuating lift is attainable. It is due to remarkable alterations of the timing and location of concentrations of vorticity in the very near-wake, relative to the instantaneous position of the cylinder during its cycle of oscillation. These phenomena are related to the direction of energy transfer between the fluid and the cylinder. All of the foregoing features are being addressed for cases of a fully-submerged cylinder and a cylinder in proximity to a free-surface.

Wake-Cylinder Interactions Due to In-Line Oscillations in Presence of a Steady Current in a Free-Surface

Long wave motion past a stationary cylinder can be simulated effectively by streamwise oscillations of a cylinder. The initial phase of this investigation considers such oscillations in presence of a steady current. In analogy with locked-on vortex formation from a transversely oscillating cylinder in a steady current, new types of locked-on vortex formation from a cylinder oscillating in the in-line direction in a steady current have been defined. In contrast to classical lock-on, the locked-on traces of transverse force fluctuation exhibit strong amplitude and frequency-modulation. Kármán-like vortex formation occurs over a portion of the locked-on cycle; during the remaining portion of this cycle, the near-wake pattern of vortices is essentially “frozen”. A further distinction of this type of lock-on is the existence of several well-defined spectral components of the transverse force fluctuation, which can span a wide range, from the subharmonic to the third harmonic, of the cylinder oscillation frequency. This feature

contrasts with the case of classical lock-on, which exhibits dominance of a single spectral component. Further interpretation of the unsteady forces is provided by various phase plane representations, which emphasize the hysteretic variations of both in-line and transverse force components and provide a basis for determining existence of negative fluid damping and work by the fluid on the cylinder. The next phase of this research will examine the consequence of an adjacent free-surface.

Wake of a Stationary Horizontal Cylinder in a Free-Surface Wave

An incident free-surface wave having elliptic particle trajectories induces classes of vortex formation distinctly different from those of a cylinder in a unidirectional, oscillating stream. During a single cycle of the wave motion, concentrations of vorticity can form at as many as three distinctly different sites about the circumference of the cylinder. These concentrations are eventually shed and undergo orbital trajectories, which appear to be dominated by the particle trajectory of the wave motion, suggesting that mutual induction effects may be second order. As a typical vorticity concentration negotiates its orbit, its peak vorticity and circulation decay relatively rapidly. Evaluations of instantaneous moments of vorticity indicate that the largest moments and changes in moments occur either for small amplitude orbits of the vorticity concentrations or during the early stage of a larger amplitude orbit. As the nominal submergence of the cylinder beneath the free-surface is altered, generic types of vortex formation from the cylinder persist. The timing and strength of these shed vortices are, however, substantially altered by the degree of submergence.

Wake of Vertical, Elastically-Mounted Cylinder in a Free-Surface Wave

A vertically-oriented cylinder is mounted on a unique elastic support, which provides circumferentially-invariant stiffness and low mass damping ratio; the design concept involves a large number of air mini-jets to suspend the system. A central issue is the degree to which the orbital nature of the incident free-surface wave can lead to organized vortex shedding from the vertical cylinder. This issue is related to the transient build-up of the oscillation, which can transform from a single mode, in-line oscillation to a distorted figure-eight pattern of the oscillation trajectory. Present emphasis is on characterization of the limit cycle behavior of the latter mode, with characterization of patterns of vorticity and streamline topology in a horizontal plane immediately beneath the free-surface of the wave. Distinctive patterns of vorticity are shed from the cylinder and, in some cases, due to the return cycle of the wave, eventually collide with the cylinder. This nature of vortex formation from the elastically-mounted cylinder is currently being assessed in relation to: the instantaneous velocity vector of the cylinder motion; and the vector of the undisturbed region of the wave. The use of sectional streamline topology techniques is expected to provide insight into the degree to which the vortex formation process is quasi-two-dimensional.

Wake Structure and Loading from Oscillating Cylinders: Effect of Three-Dimensionality of the Near-Wake

The prevailing viewpoint is that oscillation of a cylinder, at least in the region of locked-on vortex formation, gives rise to spanwise coherent vortex formation. Although this may be the case for the larger-scale modes of three-dimensionality, it is expected that small-scale three-dimensionality will still exist, and may even be enhanced, during large-amplitude oscillations. To correlate this spanwise structure of the wake with the quasi-two-dimensional structure, an orthogonal space-time imaging system has been developed. It correlates patterns of the flow in the side and end views, thereby providing an instantaneous relationship between concentrations of spanwise and streamwise vorticity.

Representative cases of vortex formation from a cylinder undergoing transverse, in-line and orbital oscillations are currently under investigation. Preliminary results indicate existence of highly concentrated streamwise vorticity with peak values as large as one-third those of the spanwise vorticity. Simultaneous measurement of the instantaneous lift and drag on the cylinder will allow interpretation of the loading in terms of the patterns of vorticity and streamline topology.

IMPACT/APPLICATIONS

The thrust of the present series of efforts is to provide a quantitative, global basis for evaluating the unsteady flow patterns about a cylinder in relation to the forces on the cylinder. This reveals the underlying physics of unsteady loading of stationary and oscillating cylinders in both steady current and waves; it also provides quantitative guidance for development of new numerical and theoretical approaches, where instantaneous, in addition to averaged, experimental representations of the quantitative flow patterns is desirable.

From a practical standpoint, the dimensionless versions of the force loading coefficients, for the various classes of unsteady wake-cylinder action addressed herein, can be used for design purposes. Such information has not been typically available for viscous-influenced forces on a body in proximity to a free-surface, with unsteadiness due to either wave motion, oscillation of a body, or a combination thereof.

The types of laser-based, quantitative visualization employed herein may also find direct application in the field. Rapid technological advances in both laser and imaging systems in the coming years will make deployment in the ocean environment an attractive possibility.

TRANSITIONS

The various types of vortex-cylinder interaction described in the foregoing have yielded instantaneous, quantitative images, which have been provided to a number of universities and government laboratories in this country and abroad. International interactions include colleagues at the Universities of Hamburg, Karlsruhe, and Stuttgart, who are particularly interested in the development of numerical approaches to this class of problems. Moreover, a number of faculty and scientists from abroad have visited our laboratories for extended periods. A program with Monash University, sponsored by the Australian Research Council, enhances these interactions.

RELATED PROJECTS

Acquisition of laser and imaging facilities has been aided by grants from the National Science Foundation and the Air Force Office of Scientific Research.

PUBLICATIONS

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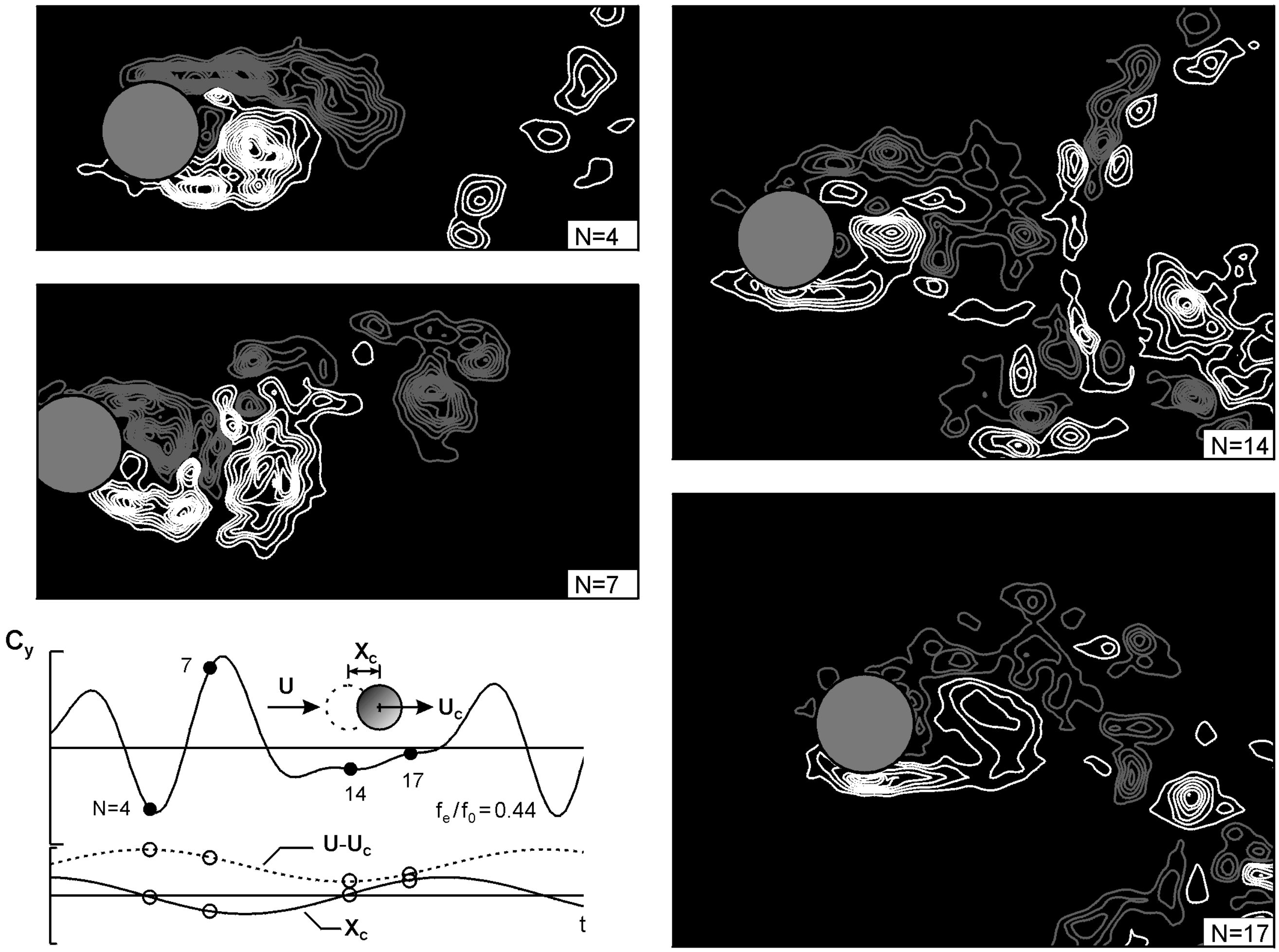

Streamwise Oscillations of a Cylinder in a Steady Current: Simulation of Long Wave Interaction with a Stationary Cylinder

In analogy with the well-known occurrence of locked-on vortex formation from a transversely-oscillating cylinder, patterns of locked-on vortices can occur from a cylinder oscillating in the streamwise direction. In this case, however, the patterns and thereby the loading are not at a single frequency. Rather, complex amplitude- and frequency-modulated, yet locked-on, vortex formation and fluctuating forces are attainable; correspondingly, the spectra of the cylinder loading exhibit a number of sharply defined peaks over a wide range of frequencies. The instantaneous trace of the transverse force exhibits a highly unusual signature: a pronounced negative, then positive peak, followed by a region of nearly zero lift. These pronounced negative and positive peaks correspond to the images N = 4 and 7, for which the cylinder is moving against the current. Over the time span between these two successive images, the initially-formed concentration of vorticity switches from the bottom to the top surface of the cylinder. In contrast, for images N = 14 and 17, the movement of the cylinder in the same direction as the current results in an essentially “frozen” pattern of vorticity concentration in the near-wake, i.e., the initially-formed vortex remains from the lower side of the cylinder.

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